Argonne NATIONAL LABORATORY

High Efficiency GDI Engine Research with Emphasis on Ignition Systems

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Argonne National Laboratory

2014 DOE Merit Review

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Project ID: ACE084

Overview

Timeline

- Project start: FY 2013
- Project end: ongoing

Budget

- Funding in FY13: $400k
- Funding in FY14: $350k

Partners

- Ford (engine hardware)
- Altronic, LLC. (DEIS ignition system)
- CSU, Seaforth, LLC. (laser ignition)
- Sandia Natl Lab (optical engine data)

Barriers

Robust lean-burn and EGR-diluted combustion technology and controls, especially relevant to the growing trend of boosting and down-sizing engines…

- Limited lean and EGR-diluted operating range
- Lack of systematic assessment of ignition systems and their potential in combination with lean/dilute combustion
- Absence of robust modeling tools

Relevance

Dilute combustion in advanced gasoline SI engines offers the greatest potential for decreasing petroleum consumption, since gasoline is the most widely produced and used fuel in the US — a trend expected to continue for the foreseeable future[1]

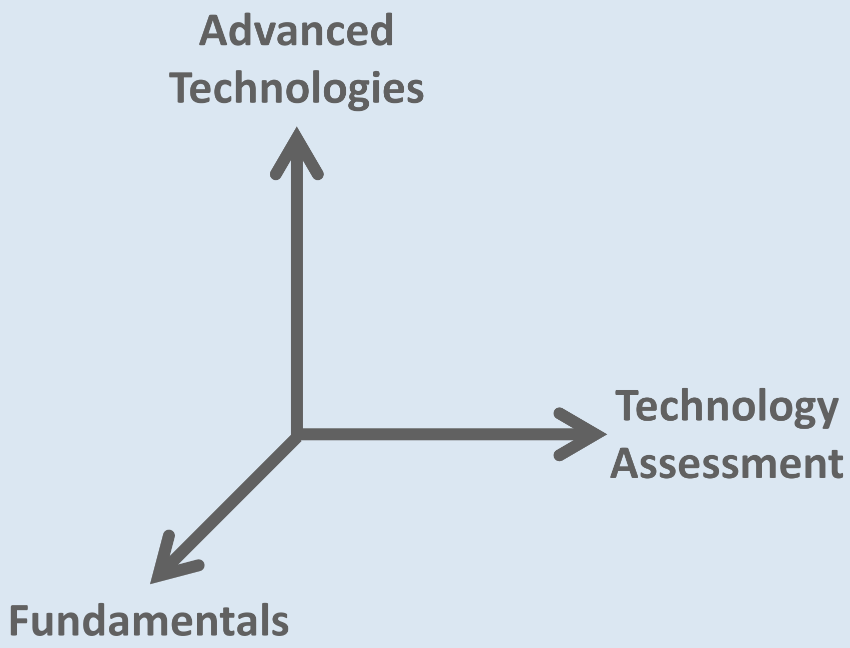
For the US market, dilute combustion currently translates to stoichiometric operation with ever increasing EGR levels

Honda R&D recently published lean-burn efficiency data
(33.7 to 39.9% ITE at 1500RPM 5 bar IMEP, AFR 14 to 30, 2000 ppm to 30 ppm NOx)[2]

Recent developments in Pumped Solid State Lasers show promise for integration in automotive Spark Ignition (SI) engine applications

[1] US DRIVE Advanced Combustion and Emission Control (ACEC) Technical Roadmap for Light-Duty Powertrains
[2] Hanabusa, H., Kondo, T., Hashimoto, K., Sono, H. et al., "Study on Homogeneous Lean Charge Spark Ignition Combustion," SAE Technical Paper 2013-01-2562, 2013, doi:10.4271/2013-01-2562

Project Objectives



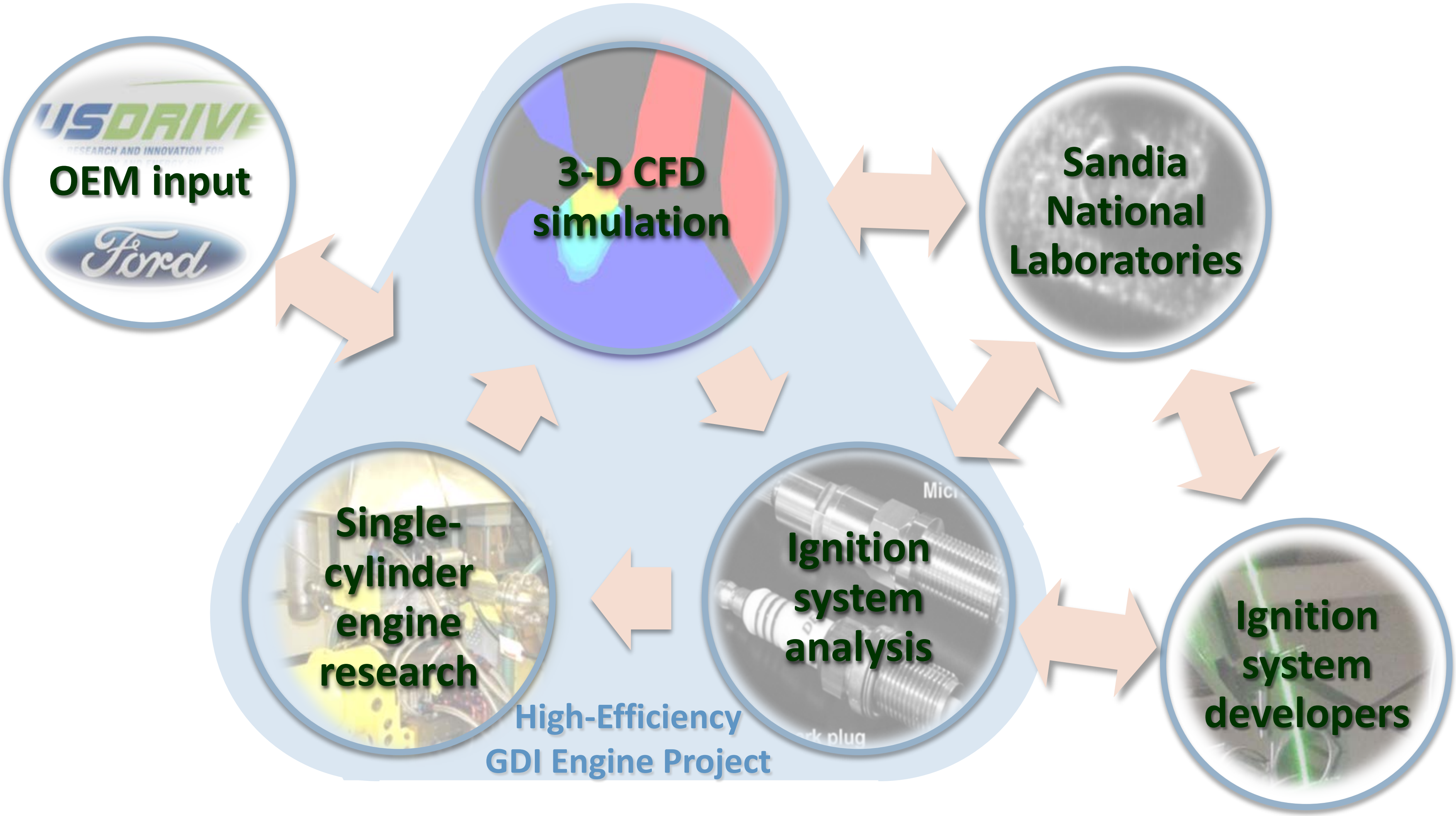
Maximize efficiency benefits and minimize NOx emissions from automotive GDI engines

- Broaden the lean and EGR-dilute operating range
- Investigate ignition systems systematically and determine compatibility with lean/dilute combustion
- Provide robust modeling tools for rapidly screening proposed designs based on sound metrics

Milestones

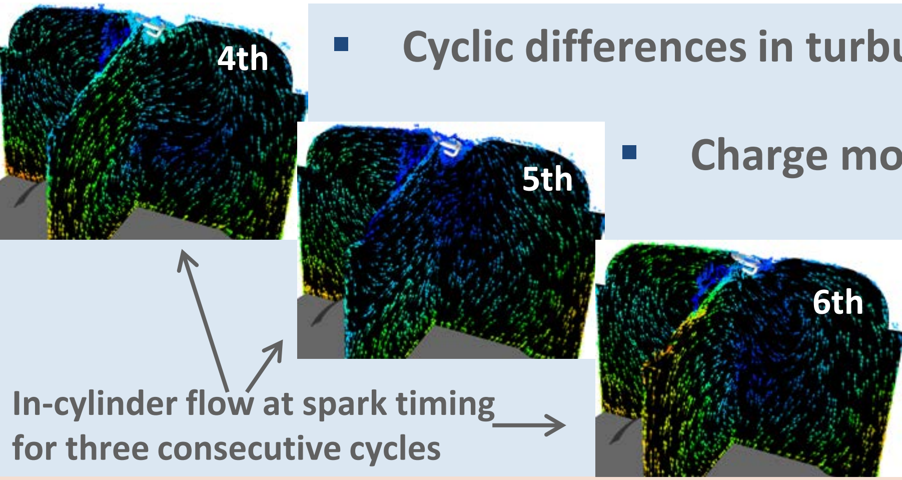
Month/Year	Description	Status
April 2013	Upgrade to spray-guided DI configuration	Complete
June 2013	Ranking of ignition systems	Complete
Sept 2013	Cyclic variability study with dilute operation	Complete
Dec 2013	Evaluation of advanced spark-based ignition systems	Complete
March 2014	Meet with Sandia to coordinate collaboration on ignition system projects	Initiated/ ongoing
June 2014	Determine applicability of RANS based 3D simulation approach for flame propagation and combustion stability under dilute (lean/EGR) operating conditions	On schedule
Sept 2014	Finalize assessment of laser ignition potential	On schedule

Approach
Organizational Integration



Technical accomplishments
Advanced RANS + multi-cycle simulations

- Cyclic differences in turbulent scales deliver variable charge motion
- Charge motion affects combustion
- Combustion affects gas-exchange



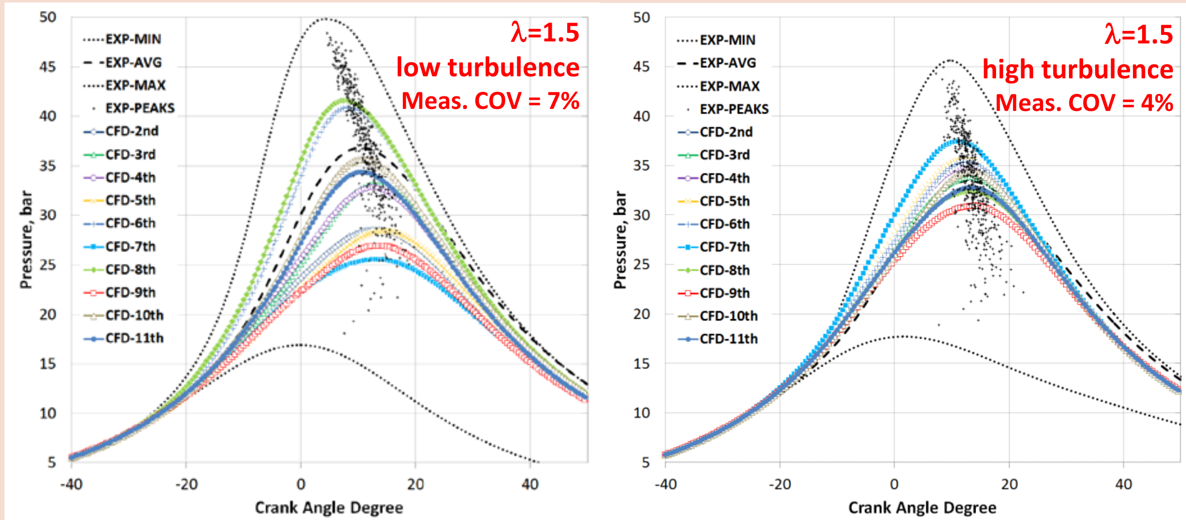
In-cylinder flow at spark timing for three consecutive cycles

Compounded effect of in-cylinder flow on flame propagation and vice versa

This is a RANS approach with similar results to LES....

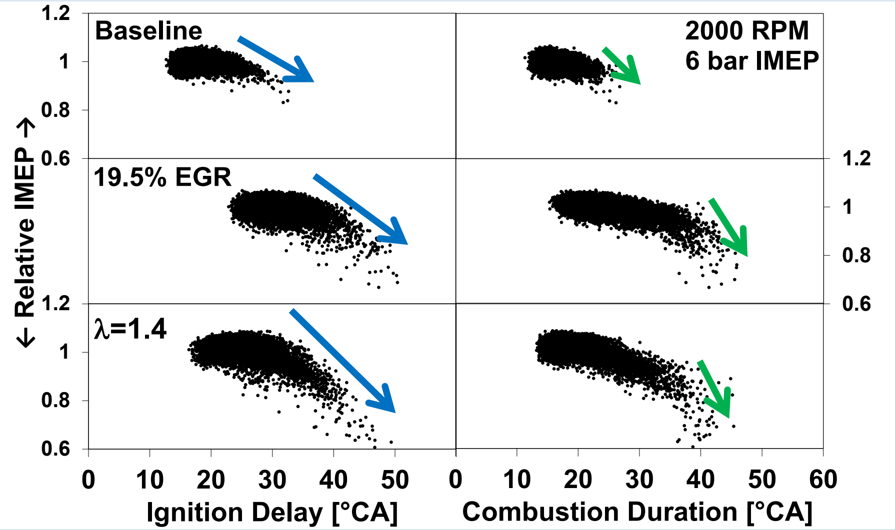
Can this approach be useful for combustion stability assessment?

- Initial test - LEAN (λ = 1.5)
  - No inhomogeneities (PFI)
  - Conventional spark system
    Different intake geometry (OPEN/CLOSE swirl plate)
  - 10 consecutive cycles (the 1st cycle is discarded)
- Trends in variation of simulation consistent with measured COV



The only difference between the two cases is the intake flow

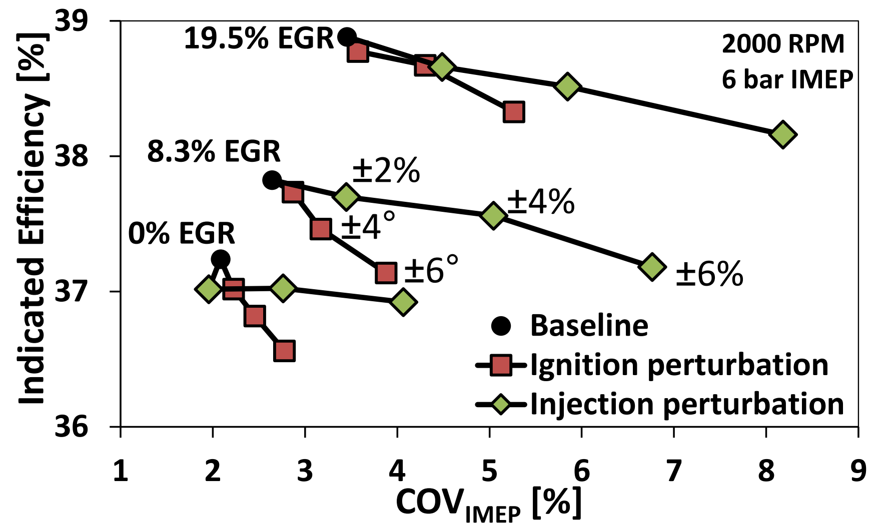
Technical accomplishments
Analysis of Cyclic Variability



- **Variability relative to position**
  - Increased ignition delay and combustion duration result in increased COV_{IMEP}
- **Within natural cyclic variability**
  - Late combustion phasing results in reduced efficiency

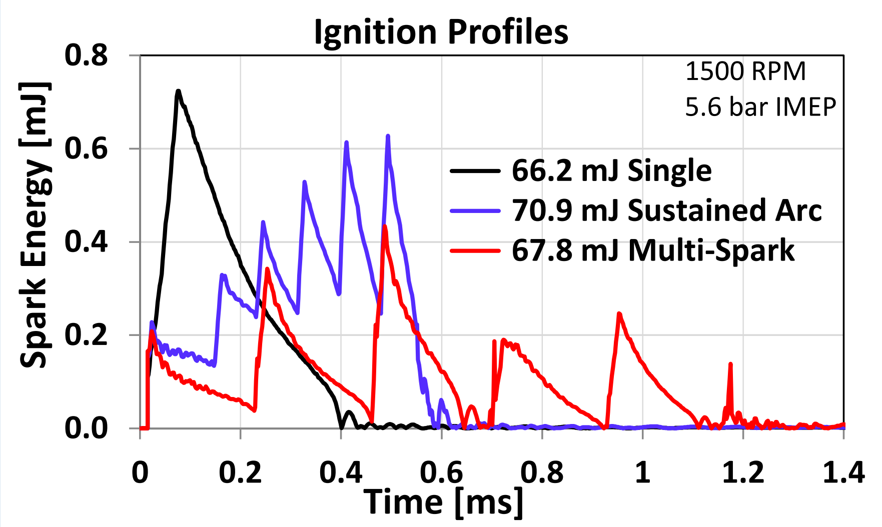
- **Control parameter sensitivity**
  - Induced perturbation on a cyclic basis
  - Ignition timing & relative air/fuel ratio
- **Higher COV_{IMEP} with injection variability**
- **Fast efficiency decay with ignition variation**
  - Ignition delay is a critical time of early flame kernel development

➢ **Alternative Ignition Concepts!**

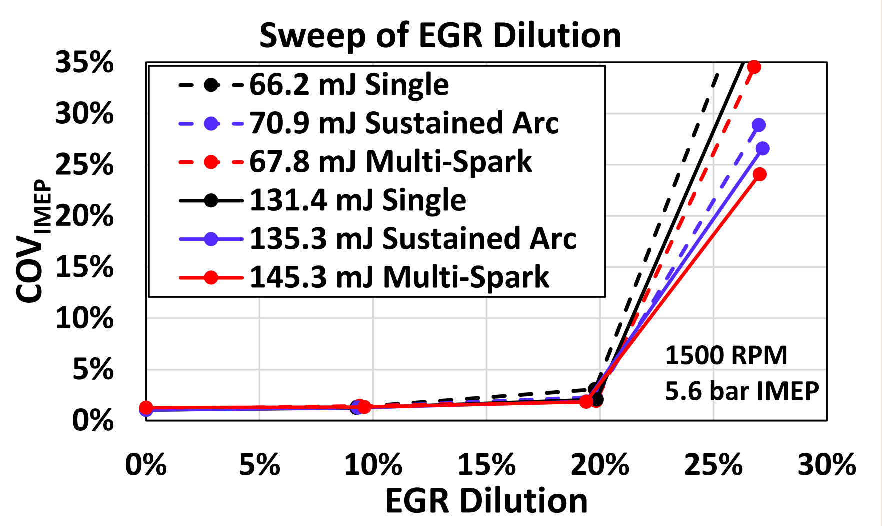


Matthias, N., Wallner, T., and Scarcelli, R., "Analysis of Cyclic Variability and the Effect of Dilute Combustion in a Gasoline Direct Injection Engine," SAE Int. J. Engines 7(2):2014, doi:10.4271/2014-01-1238.

Technical accomplishments
Alternative Spark-Based Ignition



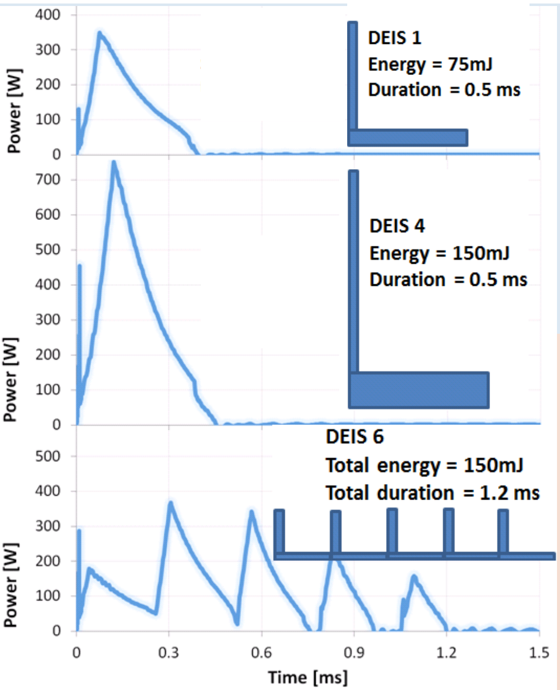
- **Several ignition concepts in one platform**
  (Altronic - Directed Energy Ignition System)
- **Ignition Energy**
  - 75 mJ & 150 mJ (nominal)
- **Alternative Ignition Profiles**
  - Sustained Arc & Multi-Spark



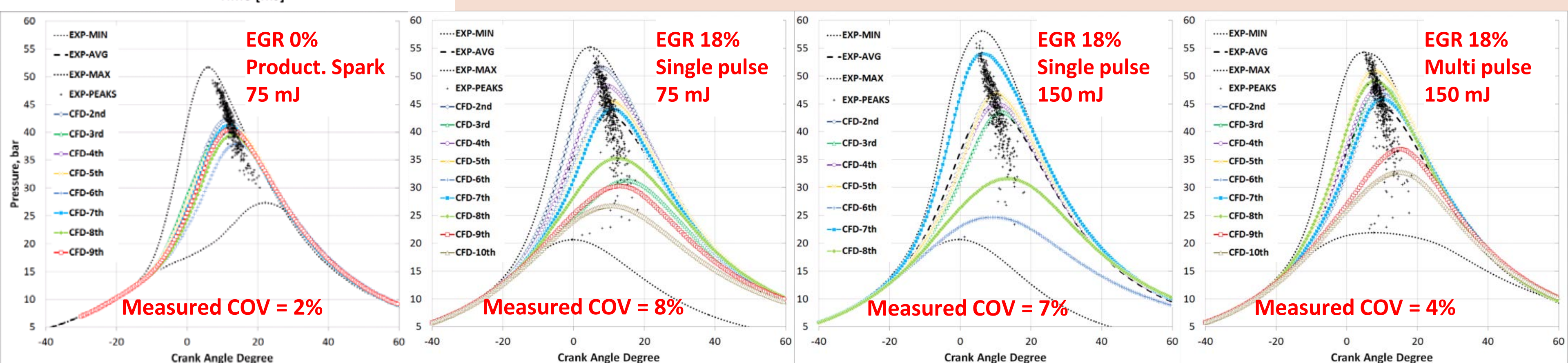
- **Differentiating ignition strategies**
  - 20-25% EGR → high COV_{IMEP}
- **Relative COV_{IMEP} improvement**
  1. Higher energy alternative profiles
  2. Lower energy alternative profiles
  3. Conventional profile
- **Alternative profiles more effective at reducing variation than increased energy**

Technical accomplishments

Modeling Alternative Ignition Profiles



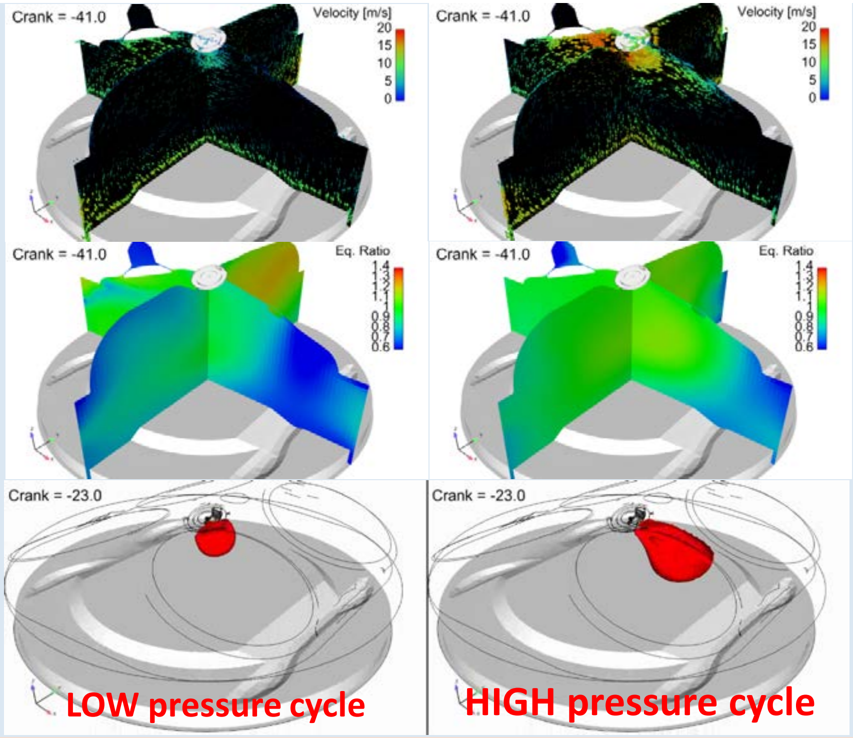
- **GDI cases with high EGR (18%)**
  - L-shaped energy transfer adapted to the ignition characteristics
  - DEIS 1 mimics conventional spark systems (75 mJ, single pulse)
  - DEIS 4 has higher energy (150 mJ, single pulse)
  - DEIS 6 has 150 mJ and multiple (5) pulses
- **Can our RANS approach capture stability trends?**
  - Current results are up to 10 cycles (1st cycle is discarded)
  - **The only difference between the operations is the ignition profile (except for baseline)**
  - **Numerical pressure variations well correlate with experimental trends**



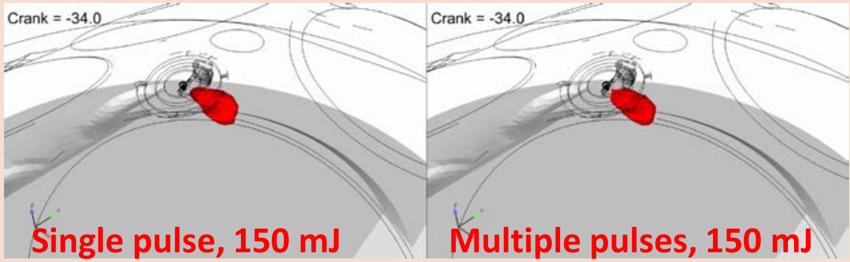
Technical accomplishments
Ignition and Cyclic Variability

- **What causes higher variability in flame propagation?**
  - Charge motion variability
  - Additional contribution of mixture distribution (GDI)
  - Combustion has an effect on next gas-exchange phase
  - PFI cases show similar variations and the charge motion was the driver

  Significant impact of charge motion (especially in the near-spark region)

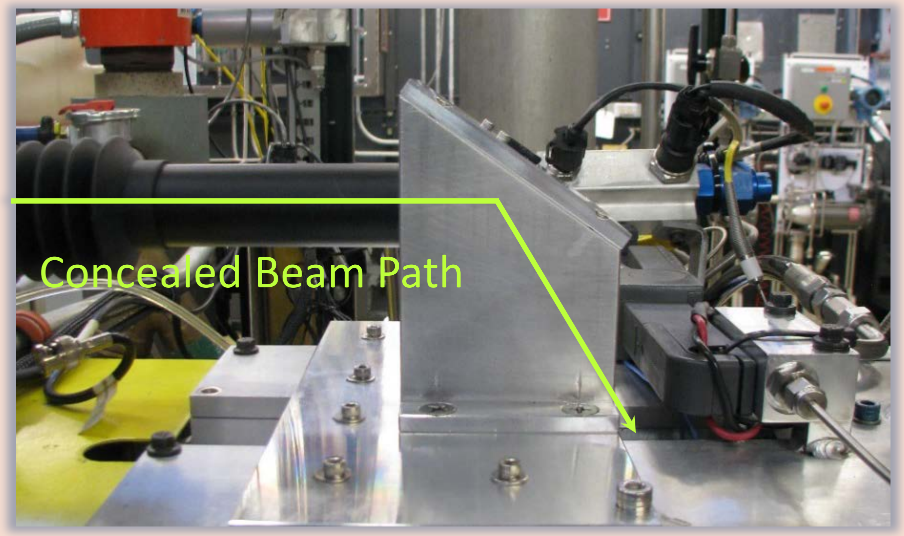


- **How do multiple pulses reduce variability?**
  - Higher energy increases the low-high amplitude
  - **Gradual energy release reduces amplitude of variations because of reduced dependence on charge motion**

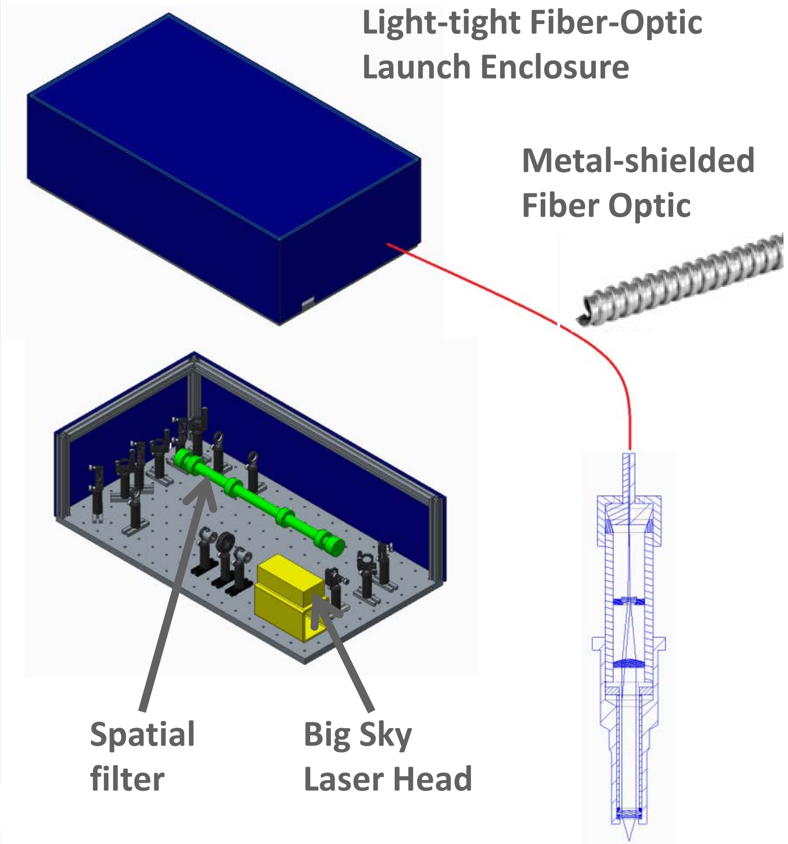


Technical Accomplishments
Laser Ignition

- **Free-Air Delivered Laser**
  - Internal collaboration
  - Quantel USA (a.k.a Big Sky Lasers)
    - 532 nm green
    - 60 mJ/pulse
    - 7-10 ns pulse width

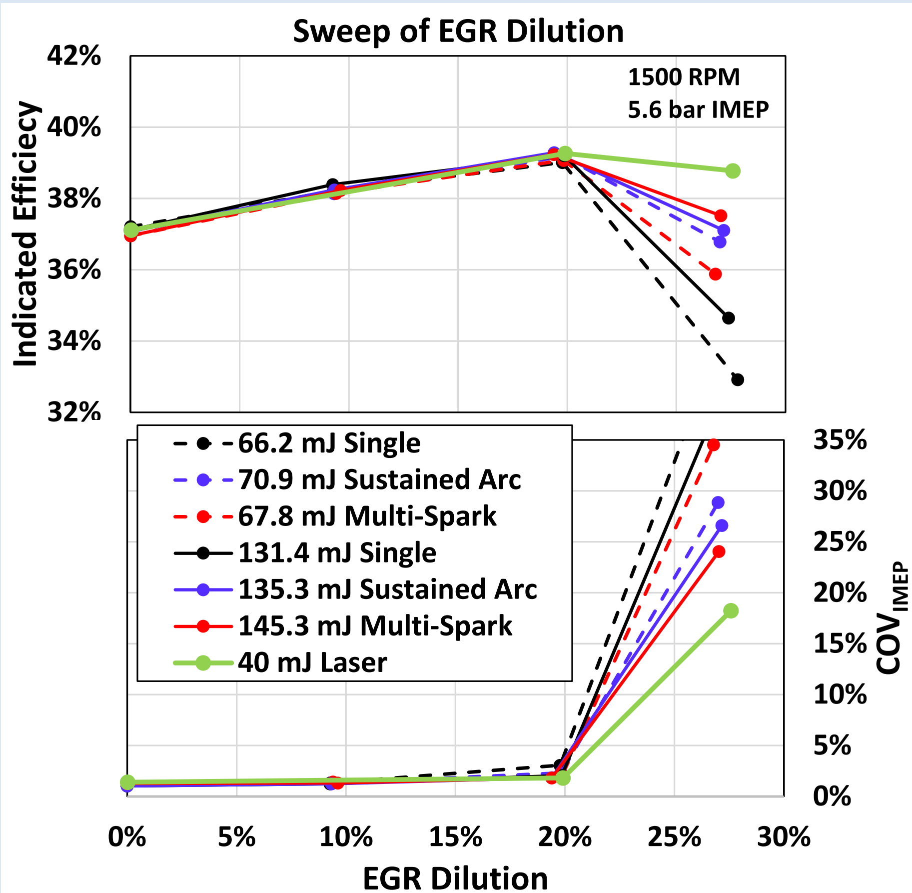


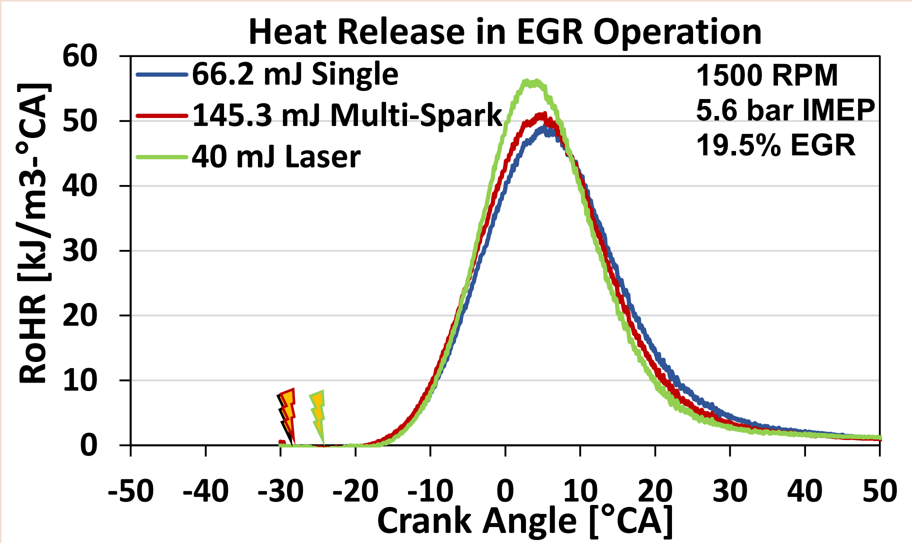
- **Fiber Optic Delivered Laser**
  - Collaboration with Colorado State University and Seaforth, LLC
  - Successful engine firing



Technical Accomplishments
Free-Air Delivered Laser

- Improved combustion stability





- Higher rate of heat release
  - Flame kernel isolation from head
  - Opportunity for optimizing ignition location (CFD input)
  - Potential for multiple ignition locations

Responses to Previous Year Reviewers' Comments

- **…an optical dimension would make this project more valuable and provide more in-depth insights.**

✓ The team has established a **collaboration with Sandia National Laboratories** (Isaac Ekoto) for optical engine data specifically related to this project. Optical data will support the CFD effort to characterize the fundamental processes of ignition and flame kernel development with alternative ignition systems.

- …**laser ignition systems applied to smaller engines could be considered new**.

✓ The team has evaluated alternative spark based ignition which serve as a point of reference for continued alternative ignition studies. **Laser ignition has been implemented and provides a pathway for more novel laser ignition concepts.**

- Reviewer was not clear **what new fundamental learning** will result from this work.

✓ The **CFD approach** is very fundamental, delivering insight into the mixture and turbulence especially in close proximity to ignition and how it relates to the flame kernel development. **Cyclic variability has been rigorously characterized** and the analysis is a framework in which to experimentally evaluate performance improvements with alternative ignition concepts.

Collaboration with Other Institutions

- **Ignition system developers**
  - Altronic, LLC: DEIS ignition system
  - CSU, Seaforth, LLC: Fiber-coupled laser ignition system (SBIR)
- **Sandia National Laboratories**
  - Fundamental ignition/combustion optical analysis
- **U.S. DRIVE Advanced Combustion & Emissions Control Tech Team**
  - Coordination and update presentations
- **In-kind Support from Ford Motor Company**
  - Engine hardware
  - Injection equipment
- **Argonne internal collaboration**
  - Benefit from extensive laser ignition expertise at DERC
  - Numerical Simulations run on Blues Cluster at LCRC

Remaining Challenges and Barriers

- A comprehensive understanding of cycle to cycle feedback mechanisms for gasoline combustion is needed to maximize efficiency specifically in dilute operation
- Fundamental understanding and predictive simulation capabilities of cyclic variability are in their infancy
- Simplified ignition models are likely not able to correctly represent advanced ignition modes/systems
- Benefits of advanced ignition systems in combination with extreme dilution are not well understood

Proposed Future Work

- Develop advanced RANS approach as a means to determine combustion stability and benchmark against LES simulations
- Continue evaluation of advanced ignition systems including laser ignition with focus on combustion stability and fundamental interactions
- Develop alternative ignition models to correctly represent advanced ignition systems in predictive simulations
- Investigate ignition/flow interactions and validate against optical results from Sandia National Laboratories

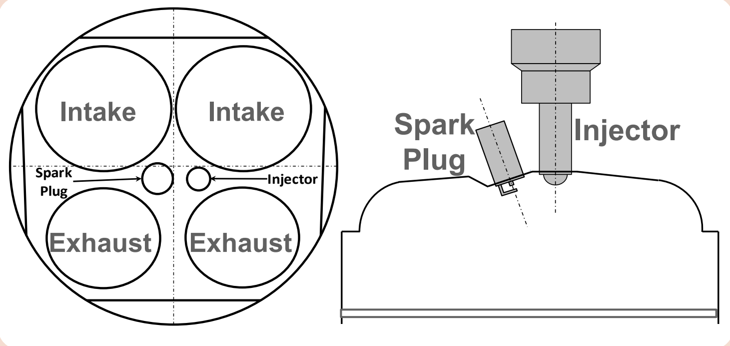
Summary

- Characterized fundamental combustion stability trade-offs as a function of dilution level (lean/EGR)
- Assessed the effect of sustained and multi-spark modes for different energy levels
- Identified promising approach to predicting cyclic variability using advanced RANS simulations
- Successfully implemented and demonstrated laser ignition system on single-cylinder research engine platform

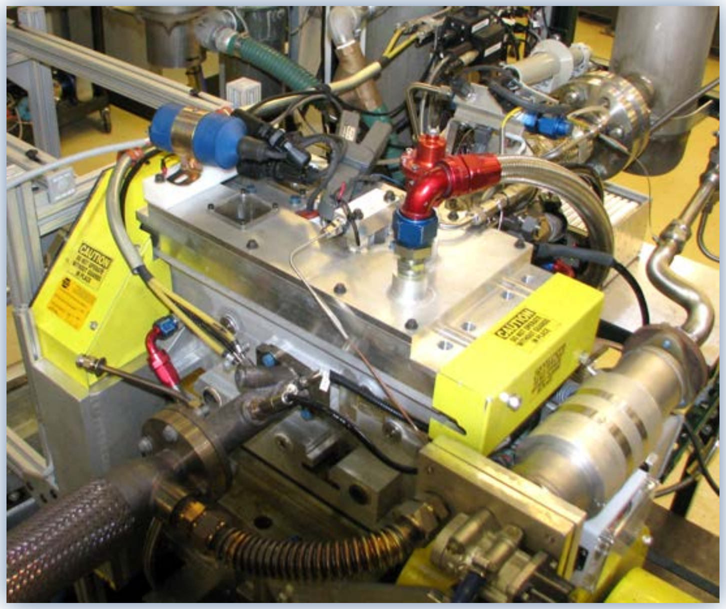
Technical Back-Up Slides

Engine Setup
State-of-the art GDI Engine

- **Typical SI combustion chamber design**
  - 140° pent roof head, flat piston top, central spark plug and injector
- **External high pressure gasoline pump**
  - Up to 200 bar injection pressure

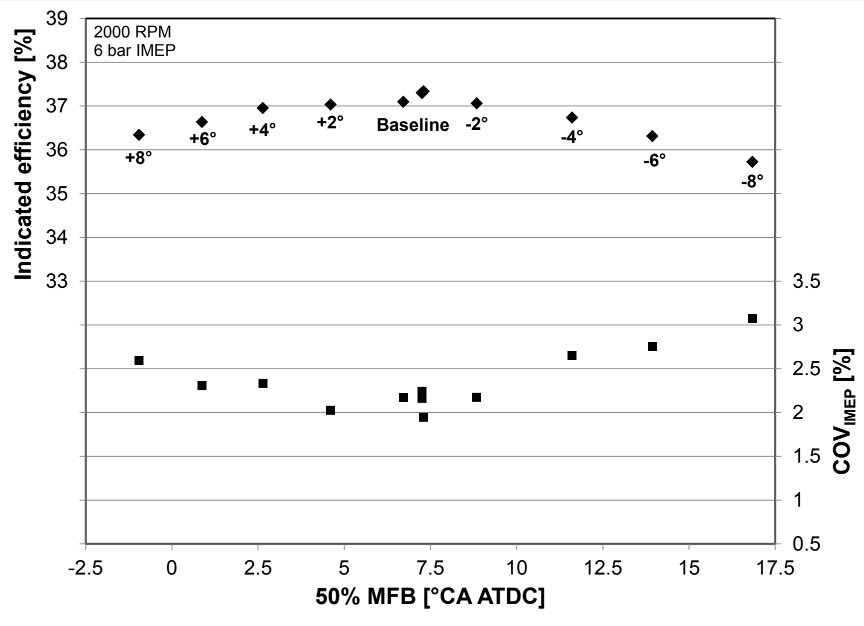


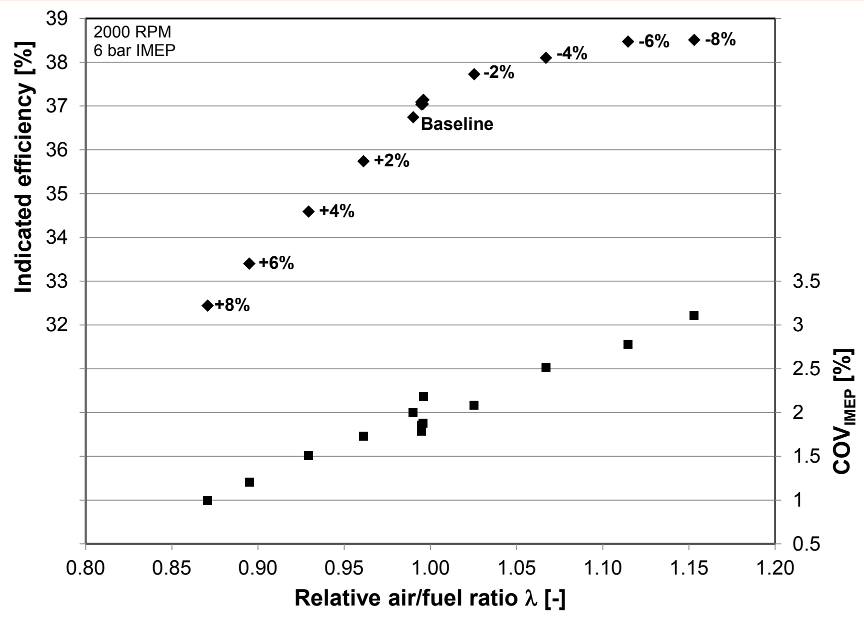
- **High Speed Secondary Coil Voltage**
  - ~1 nanosecond breakdown phase
  - 2.4 kV in-cylinder breakdown
  - Up to 40 kV measurement
- **Simultaneous Current Measurement**
  - Enables high fidelity power measurements to quantify ignition energy



GDI Engine Specifications	
Displacement	0.626 L
Bore/Stroke	89/100.6 mm
Compression Ratio	12.1
Intake Valve MOP	100 °CA ATDC
Exhaust Valve MOP	255 °CA ATDC
GDI Injector	6 hole, solenoid
Injection pressure	150 bar
Spark Plug	NGK-R dual fine wire, 0.7 mm gap
Fuel	EPA Tier II EEE

Control Parameter Sensitivity
Baseline for Perturbation Cases





- Combustion Phasing
  - 7.5 °CA is optimal
  - Early and late phasing both decrease efficiency and increase COV_{IMEP}

- Relative Air/Fuel Ratio
  - $\lambda < 1$ not only decreases efficiency but also COV_{IMEP}
  - $\lambda > 1$ improves efficiency but with greater COV_{IMEP}

Matthias, N., Wallner, T., and Scarcelli, R., "Analysis of Cyclic Variability and the Effect of Dilute Combustion in a Gasoline Direct Injection Engine," SAE Int. J. Engines 7(2):2014, doi:10.4271/2014-01-1238.

Simulation Details
CFD features

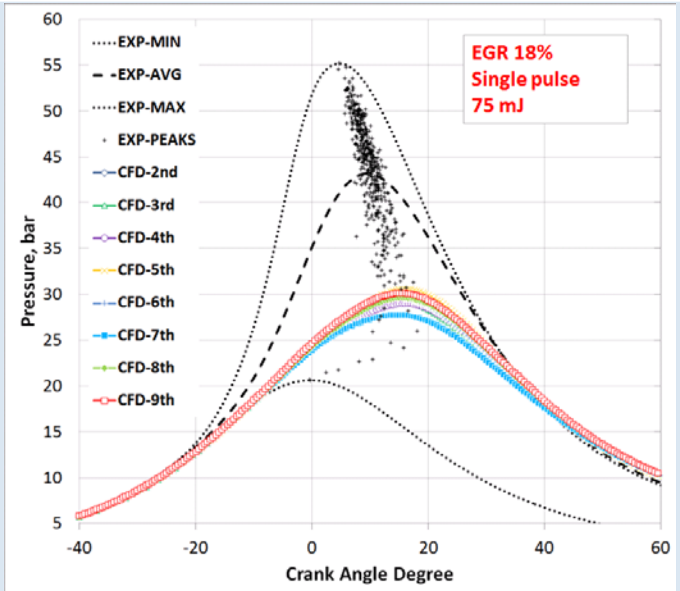
CONVERGE™ from Convergent Science, Inc.

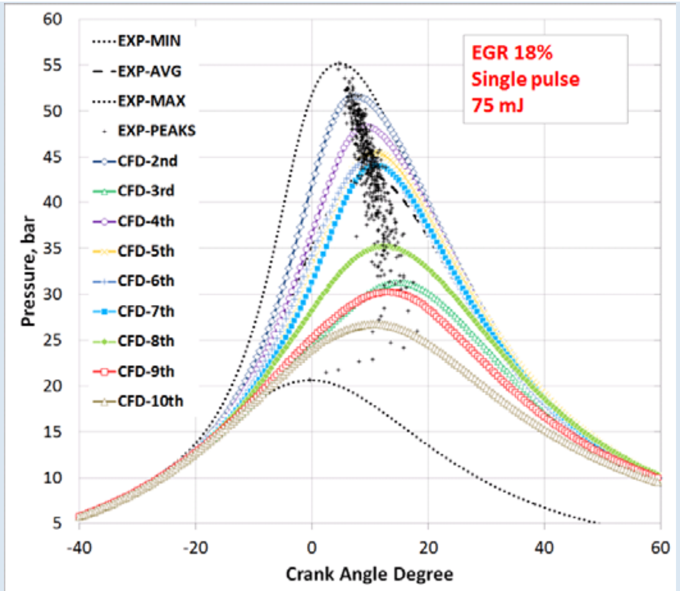
- **Orthogonal grid with advanced refinement algorithm**
  - ✓ Base grid = 4 mm
  - ✓ Fixed Embedding where needed (chamber, valve seats, spark-plug)
  - ✓ AMR based on Temperature and Velocity gradients
  - ✓ **Cell size during combustion = 0.125 mm (spark) – 0.5 mm (flame)**
  - ✓ High accuracy with reasonably small grids (1,200,000 cells maximum)
  - ✓ One cycle simulated in 36-48 hrs on 24-64 cores
- **2nd order accuracy for the momentum equation (central scheme)**
- **RANS approach, k-ε RNG model for turbulence**
- **Energy deposition model (L-type, 0.5 mm sphere)**
- **Direct Chemistry (Arrhenius + detailed chemistry) → No turbulent sub-grid term in the reaction rate**
- **Multi-zone model to speed up the calculations involving kinetics**

Simulation Details
Effect of grid resolution on cyclic variability

CONVENTIONAL
NO AMR
(adaptive mesh refinement)

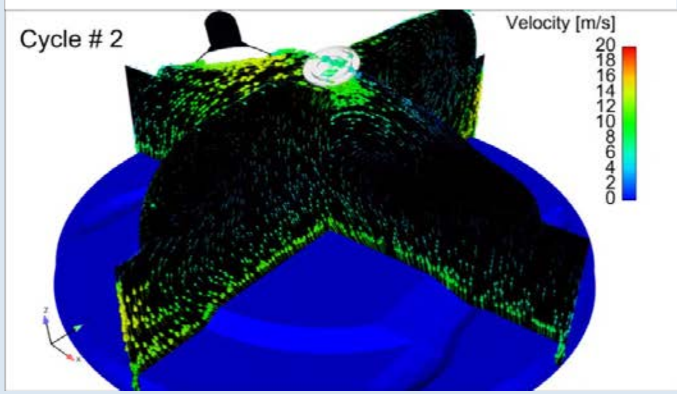
Grid resolution:
- Spark1 0.25mm
- Spark2 0.5mm
- Flame 1mm
- Flow 1mm
- Cylinder 1mm

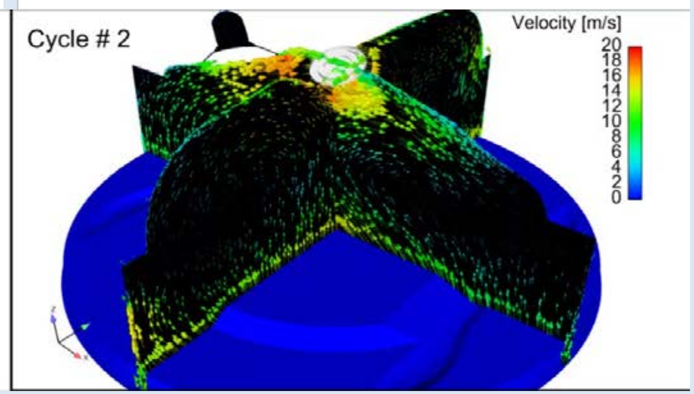




ADVANCED
WITH AMR

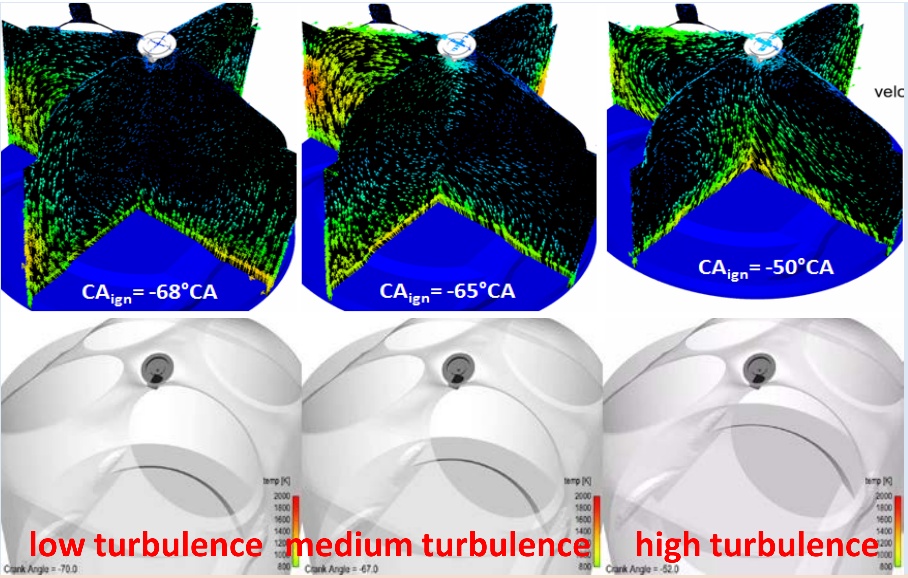
Grid resolution:
- Spark1 0.12mm
- Spark2 0.25mm
- Flame 0.5mm
- Flow 0.5mm
- Cylinder 1mm





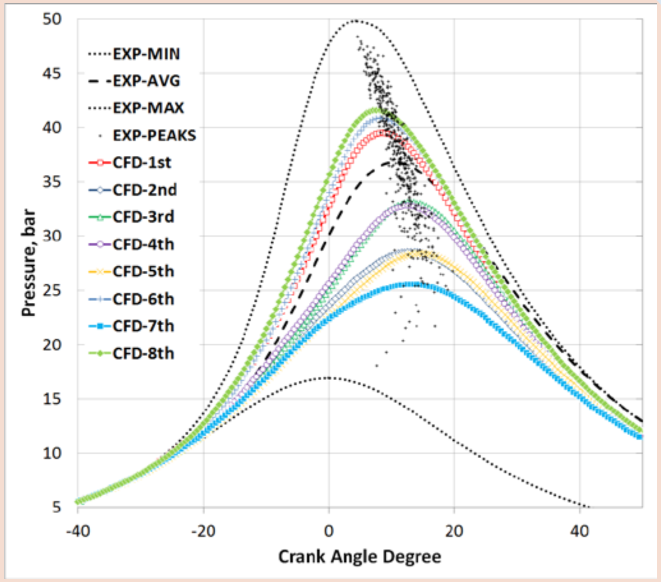
Conventional RANS (low mesh resolution - no AMR) does not deliver significant fluctuation of numerical results but needs a turbulent sub-grid term (TCI) to simulate combustion properly

Simulation Details
CFD Model Validation



- **Lean and EGR dilute SI combustion**
  - Reliable mechanism (LLNL-lowP) and fine mesh are needed*
  - Flame propagation and interaction with the flow well described even using Direct Chemistry*
- **Effect of intake flow on combustion**
  - Importance of near-spark flow
  - Tumble preferred over swirl
- **Validation against engine data**
  - Numerical results show no convergence of pressure traces
- **RANS with low numerical diffusion**
  - Difference in turbulent scales due to the effect of each cycle on the next → Low numerical diffusion does not damp out the variability in large structures from cycle to cycle

Multi-cycle simulations and qualitative validation against 500 cycles



* Scarcelli, R., Matthias, N., and Wallner, T., 2013-24-0029